

Electrocardiogram-gated coronary CT angiography dose estimates using ImPACT

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The primary study objective was to assess radiation doses using a modified form of the Imaging Performance Assessment of Computed Tomography (CT) scanner (ImPACT) patient dosimetry for cardiac applications on an Aquilion ONE ViSION Edition scanner, including the Ca score, target computed tomography angiography (CTA), prospective CTA, continuous CTA/cardiac function analysis (CFA), and CTA/CFA modulation. Accordingly, we clarified the CT dose index (CTDI) to determine the relationship between heart rate (HR) and X-ray exposure. As a secondary objective, we compared radiation doses using modified ImPACT, a whole-body dosimetry phantom study, and the k-factor method to verify the validity of the dose results obtained with modified ImPACT. The effective dose determined for the reference person (4.66 mSv at 60 beats per minute (bpm) and 33.43 mSv at 90 bpm) were approximately 10% less than those determined for the phantom study (5.28 mSv and 36.68 mSv). The effective doses according to the k-factor ($0.014 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$; 2.57 mSv and 17.10 mSv) were significantly lower than those obtained with the other two methods. In the present study, we have shown that ImPACT, when modified for cardiac applications, can assess both absorbed and effective doses. The results of our dose comparison indicate that modified ImPACT dose assessment is a promising and practical method for evaluating coronary CTA.

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Key words: computed tomography, ImPACT, effective dose, organ dose, coronary CT angiography

I. INTRODUCTION

Coronary computed tomography angiography (CCTA) is considered a reliable practical diagnostic method for coronary artery disease. Although an estimated 410,000 examinations are performed annually at 1,535 cardiology and/or cardiovascular surgery hospitals in Japan,⁽¹⁾ CCTA can be harmful to patients because of the risk associated with a potential high radiation dose. According to a 2008 report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), effective doses of CCTA range from 3 to 27.5 mSv.⁽²⁾ This effective dose range is wider than that of other CT examinations: head, 0.9–7.9 mSv; chest, 2.2–12.9 mSv; abdomen, 3.1–16.1 mSv. In addition, the effective dose of CCTA is higher than that

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of other CT examinations; therefore, appropriate dose management is needed. These effective doses were determined using a number of estimation methods, including a whole-body dosimetry phantom study with a thermoluminescent dosimeter (TLD)^(3,4) and a number of dosimetric application software studies such as the ImpactDose CT application (VAMP GmbH, Erlangen, Germany) with standardized male and female anthropomorphic mathematical phantoms.^(5,6) The phantom study represents a sophisticated clinical method. However, the absorbed and effective doses are obtained easily with the ImpactDose application, as the software can select cardiac scan protocols from a “User-specified” or “SOMATOM Definition Flash scanner” during CCTA examinations.⁽⁷⁾ Although the ImpactDose has enabled better estimations of effective dose using the ICRP Publication 110 reference male and female phantoms,⁽⁸⁾ the relationships between heart rate (HR) and cardiac scan protocols have not yet been clarified. In contrast, the Society of Cardiovascular Computed Tomography (SCCT) has published CCTA guidelines to facilitate reliable estimations of practical effective doses.⁽⁹⁻¹¹⁾ In the SCCT guidelines,⁽⁹⁾ the dose-length product (DLP) — which has accordingly been defined by a number of international organizations including the International Commission on Radiological Protection (ICRP),^(12,13) European Commission,^(14,15) and International Electrotechnical Commission⁽¹⁶⁻¹⁸⁾ — has been recommended as the most useful parameter for dose estimation. A reasonable method (k-factor; adult chest $0.014 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$) for estimating the effective dose was introduced in the 2004 European Commission guidelines.⁽¹⁴⁾ However, this k-factor represents a change from the value of $0.017 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$ reported in the 2000 guidelines⁽¹⁵⁾ because the value of effective dose was evaluated by new tissue weighting factor. For this reason, k-factor may be revised. Moreover, a study by Einstein et al.⁽¹⁹⁾ has better elucidated the cardiac k-factor ($0.027\text{--}0.034 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$), which is important because the adult chest k-factor tended to underestimate the effective dose for CCTA. However, the k-factor is limited by its lack of assessment of organ- and/or tissue-absorbed doses.

To date, little information has been reported regarding electrocardiogram (ECG)-gated scanning-based dose assessment methods.⁽²⁰⁾ However, one of the primary CT dose assessment software is the Imaging Performance Assessment of CT scanner (ImPACT) patient dosimetry version 1.04 software (released in May 2011; Scanner Evaluation Centre of the United Kingdom National Health Service), which could not estimate the CCTA dose.⁽²¹⁾

The primary objective of this study was to assess radiation doses using modified ImPACT for cardiac applications (e.g., Ca score, target CTA, prospective CTA, continuous CTA/cardiac function analysis (CFA), and CTA/CFA modulation), as described by Kobayashi et al.,⁽²¹⁾ on an Aquilion ONE ViSION Edition scanner (Toshiba Medical Systems, Otawara, Japan). For these processes, we clarified the CTDI to determine the relationship between HR and X-ray exposure when using cardiac applications. As a secondary objective, we compared radiation doses determined using modified ImPACT, a whole-body dosimetry phantom study, and the k-factor study, to evaluate the practicality of modified ImPACT.

II. MATERIALS AND METHODS

A. Conversion factor evaluation

A multidetector row CT (MDCT) scanner with 320 rows of detector elements (320-MDCT, Aquilion ONE ViSION Edition), which is capable of data acquisition at a slice thickness of 0.5 mm and coverage of 160 mm, was used in this study. The applicable CTDI for each of the scan protocols was obtained from the CT console display, as summarized in Table 1. The conversion factor (C.F.) was then determined according to the following equation:

$$C.F. = \frac{CTDI_{with\ ECG}}{CTDI_{without\ ECG}} \quad (1)$$

where $CTDI_{without\ ECG}$ is the standard CTDI with one rotation scan, as defined by a number of international organizations,⁽¹²⁻¹⁸⁾ and $CTDI_{with\ ECG}$ is the CTDI normalized with a single-rotation ECG-gated scanning (not one rotation) of the cardiac applications (Ca score, target CTA, prospective CTA, continuous CTA/CFA, and CTA/CFA modulation).

TABLE 1. Scan protocols used for the C.F. evaluation.

	<i>Ca Score</i>	<i>Target CTA</i>	<i>Prospective CTA</i>	<i>Continuous CTA/CFA</i>	<i>CTA/CFA Modulation</i>
Tube Voltage (kV)	120	120	120	120	120
Tube rotation time (s/rot)	0.275	0.275	0.275	0.275	0.275
Target cardiac phase (%)	40 or 75 ^a	40 or 75 ^a	0-99 int. 1	0-100	0-100
Acquisition time (s)		0.275-0.4			
Dose reduction (%)					5-80
Dose reduction phase (%)					0-99 int. 1
Heart rate (bpm)	40-120	40-120	40-120	40-120	40-80

^a Cardiac phase is 75% of the R-R interval (late diastole) for 40-60 bpm or 40% (end systole) for 70-120 bpm.

B. Cardiac applications

The 320-MDCT has cardiac applications of the prospective ECG-triggering scans (Ca score, target CTA, and prospective CTA) and retrospective ECG reconstruction scans (continuous CTA/CFA and CTA/CFA modulation) as are explained in sections B.1 to B.5 below. Completely different scan techniques are used in accordance with the patient's HR and the purposes to reduce their radiation dose. It is common knowledge that these scan timings of scan techniques are closely related to HR. According to previous publications, the optimal cardiac phase is generally 75% of the R-R interval (late diastole) for HR 40–60 beats per minute (bpm) or 40% (end systole) for 70–120 bpm.⁽⁹⁻¹¹⁾ When HR was increased, the T-P interval gradually shortened; therefore, coronary artery only has low motion in the interval of late diastole (T-P interval) at low HR beats and end systole (Q-T interval) at high HR beats. For this reason, an HR gradient of 40–120 bpm in 1 bpm increments was used to estimate $CTDI_{with\ ECG}$, except for modulation, for which an HR gradient of 40–80 in 1 bpm increments was used. Because of the modulation did not work in high HR. All $CTDI_{with\ ECG}$ values were obtained from the CT console display.

B.1 Ca score

The Ca score (a Framingham Risk Score) is an effective index for determining the appropriate program to treat the amount of Ca in coronary arteries. This is a low-dose scanning technique involving the exposure time and a single cardiac phase. Therefore, $CTDI_{with\ ECG}$ is obtained during the prespecified phases of late diastole (40–70 bpm) and end systole (60–120 bpm).

B.2 Target CTA

Target CTA is a low-dose scanning technique in which the exposure time and a single cardiac phase are manually preset before scanning to ensure that the patient receives consistent exposure. The actual exposure time depends on the acquisition time (i.e., absolute time; 0.275, 0.3, 0.35, and 0.4 s). Therefore, this scan mode cannot correspond to arrhythmia. $CTDI_{with\ ECG}$ for this method is obtained during the same as phase as the Ca score according to the acquisition time.

B.3 Prospective CTA

Prospective CTA is a low-dose scanning technique in which exposure occurs only during the prespecified range of the cardiac phase.^(9,10) Therefore, the actual exposure time varies according to the patient's HR. In addition, multisegmental reconstruction is available for patients with high HRs in whom multiple beats are scanned. With prospective CTA, $CTDI_{with\ ECG}$ is obtained

during the prespecified cardiac phase range of 1%–99% in 1% increments (i.e., all cardiac phase ranges, but less than a continuous scan).

B.4 Continuous CTA/CFA

Continuous CTA/CFA is a scanning technique in which exposure occurs throughout the R-R interval over one or more heartbeats. Therefore, a functional analysis can be performed using the obtained data. Similar to prospective CTA, multisegmental reconstruction is available for patients with high HRs in whom multiple beats are scanned. In this scan mode, $CTDI_{with ECG}$ is obtained throughout the cardiac cycle (0%–100%; R-R interval). In general, only data acquired during the cardiac phase with the least amount of motion are used for image reconstruction.

B.5 CTA/CFA modulation

CTA/CFA modulation is a scanning technique in which exposure occurs throughout the R-R interval and over one or more heartbeats. Exposure is also available to reduce the mA during portions of the R-R interval that do not require high-resolution imaging. Therefore, $CTDI_{with ECG}$ is obtained as follows: the tube current decreases automatically, except for the prespecified dose increase phase of 1%–99%. In this case, the 100% phase was not estimated because the tube current was fixed at that point. The dose reduction rate ranges from 5% to 80%. The C.F. is subsequently calculated using Eq. (1).

C. IMPACT patient dosimetry

IMPACT patient dosimetry spreadsheet software, version 1.0.4 for Excel (Microsoft Corp., Redmond WA, USA), was developed by the IMPACT group to provide a convenient user interface for determining organ- and tissue-absorbed doses according to the National Radiological Protection Board SR250 Monte Carlo dose data sets (NRPB-SR250) (Fig. 1).^(22,23) IMPACT reflects the further development of a method to map results from the original 23 scanner datasets

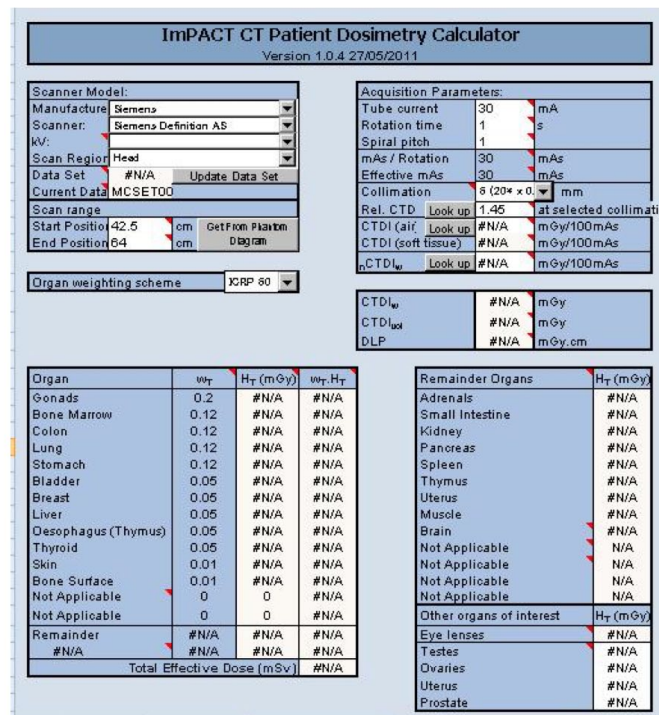


FIG. 1. Schema of IMPACT ver. 1.0.4 released 27/05/2011.

to other CT scanners by applying so-called “ImPACT factors” on the basis of tube voltage-dependent CTDI in free air ($CTDI_{air}$) and CTDI in the center ($CTDI_{100,c}$) with either a standard head or standard body polymethylmethacrylate (PMMA) phantom. The Medical International Radiation Dose Radiation dose-five (MIRD-5) mathematical phantom used in ImPACT was divided from head to mid-thigh into 208 axial slabs of 5 mm thick.⁽²⁴⁾

General usage for assessing the radiation dose (e.g., CTDI, DLP, organ/tissue absorbed dose, effective dose) was determined according to the following parameters: CT scanner, tube voltage, tube current, rotation time, spiral pitch, collimation, scan range, scan region (head or body), and organ weighting scheme, as described in ICRP 60⁽²⁵⁾ or 103.⁽²⁶⁾

D. Modification of ImPACT patient dosimetry

Macro security on the developer tab of Excel and all macros under macro settings were clicked on to enable them. In addition, to unlock any cell or spreadsheet, unprotect sheet in the review tab in the changes group was clicked. Before our study, a 320-MDCT scanner data, which was reported by Kobayashi et al.,⁽²¹⁾ was added to the database of ImPACT. A checkbox, combo boxes, and text boxes were added to assess the $CTDI_{without\ ECG}$ of cardiac applications in the ImPACT ScanCalculation worksheet (Fig. 2). The following protocols were added: scan mode, HR, cardiac phase range, and scan heartbeats. In some scan modes, acquisition time, dose reduction, and dose reduction range were necessary. To use these boxes, an ECG worksheet and a C.F. worksheet were added (Fig. 3). The ECG worksheet had reference data for select subject of cardiac application on ScanCalculation worksheet and C.F. data from C.F. worksheet. The C.F. worksheet had $CTDI_{without\ ECG}$ and $CTDI_{with\ ECG}$ data of cardiac applications. If the checkbox of ECG gate scan was active, the $CTDI_{with\ ECG}$ was selected on the C.F. worksheet, and C.F. was assessed according to Eq. (1). The result of C.F. was reflected on the ECG worksheet. $CTDI_{ImPACT\ with\ ECG}$ of “ECG Gate Scan Dose Estimation (Fig. 2)” was assessed according to the following equation:

$$CTDI_{ImPACT\ with\ ECG} = CTDI_{ImPACT\ without\ ECG} \times C.F. \quad (2)$$

where $CTDI_{ImPACT\ without\ ECG}$ is the assessment result of the original ImPACT. The $CTDI_w$, $CTDI_{vol}$, and DLP dose assessments were then weighted using the C.F. to obtain the

Scanner Model:		Acquisition Parameters:	
Manufacturer:	Toshiba	Tube current	250 mA
Scanner:	Toshiba Aquilion ONE vision edit	Rotation time	0.275 s
kV:	120	Spiral pitch	1
Scan Region:	Body	mAs / Rotation	68.75 mAs
Data Set	MCSET05	Effective mAs	68.75 mAs
Current Data	MCSET05	Collimation	140 mm
Scan Range		Rel. CTDI	Look up 0.83 at selected collimation
Start Position	43.5 cm	CTDI (air)	Look up 29.7 mGy/100mAs
End Position	53 cm	CTDI (soft tissue)	31.8 mGy/100mAs
Organ weighting scheme	ICRP 103	CTDI _w	Look up 6.3 mGy/100mAs
ICRP110 Reference Phantom Conversion Factor		Dose Estimates:	
Weighting factor by Zhang	Chest-Pelvis,M	CTDI _w	5.7 mGy
AAPM Task Group 204 Effective Diameter		CTDI _{vol}	5.7 mGy
<input checked="" type="radio"/> Lateral	8 cm	DLP	54 mGy.cm
<input type="radio"/> Anterior-posterior	8 cm	Size-Specific Dose Estimates (SSDE):	
<input type="radio"/> Lateral+Anterior-posterior	8 cm	CTDI _w	7.4 mGy
Effective Diameter	13.10 cm	CTDI _{vol}	7.4 mGy
Conversion factor	1.31	DLP	71 mGy.cm
ECG Gate Scan		ECG Gate Scan Dose Estimates:	
Scan mode	Prospective CTA	CTDI _{w,ECG}	5.9 mGy
HR	50 bpm (40-120)	CTDI _{vol,ECG}	5.9 mGy
Start Phase	70 %	DLP _{ECG}	56 mGy.cm
End Phase	80 % (0-Next R)	ECG-Size-Specific Dose Estimates (SSDE):	
Acquisition time	s	CTDI _{w,ECG}	7.7 mGy
Reduction	1 %	CTDI _{vol,ECG}	7.7 mGy
Beat	1 (1-5)	DLP _{ECG}	73 mGy.cm

Fig. 2. Schema of modified ImPACT. To use ECG gate scan mode, an ECG worksheet and C.F. worksheets were added.

C.F.-weighted absorbed doses and effective dose. In addition, several scans of CCTA are performed, such as plain scan, bolus tracking scan, and contrast enhancement scan. Therefore, a total dose worksheet and a total area worksheet were added (Figs. 4 and 5). These worksheets were linked such that the input was entered on ScanCalculation worksheet of scan protocols and an output was obtained as results of doses.

ECG gate scan:	3	TRUE	ECG factor
1	Ca scoring	CA	1.0
2	Target CTA	TA	0.0
3	Prospective CTA	PR	1.0
4	Continuous CTA/CFA	CO	4.6
5	Moduration CTA/CFA	MO	3.3
Current Selection:		PR	1.0

Beat	1	
1	1	
2	2	
3	3	
4	4	
5	5	
Current Selection:		1

FIG. 3. Schema of an ECG and a C.F. worksheet. The ECG worksheet has reference data of select subject of cardiac application on ScanCalculation worksheet and C.F. data from C.F. worksheet. The C.F. worksheet has a $CTDI_{without ECG}$ and $CTDI_{with ECG}$ data of cardiac applications.

	A	B	C	D	E	F	G	H	I	J	K	L
36		DLP	239.3738	-27.8721	129.0741							
37	Size-Specific Dose Estimates (SSDE) (mGy):	CTDIw	20.80711	15.74773	11.21952							
38		CTDIvol	20.80711	15.74773	11.21952							
39		DLP	270.4924	-31.4955	145.9538							
40	ECG Gate Scan Dose Estimates (mGy):	CTDIw/ECG	1.995796	#N/A	28.36794							
41		CTDIvol/ECG	1.995796	#N/A	28.36794							
42		DLPECG	29.51453	#N/A	369.7532							
43	ECG-Size-Specific Dose Estimates (SSDE) (mGy):	CTDIw/ECG	2.243904	#N/A	32.05577							
44		CTDIvol/ECG	2.243904	#N/A	32.05577							
45		DLPECG	29.17075	#N/A	416.725							
46	Organs (HT):	Gonads	0.002373	0.000228	0.034296							
47		Bone Marrow	0.301951	0.33	4.285714							
48		Colon	0.023725	0.0086	0.342857							
49		Lung	1.294118	1.4	18							
50		Stomach	1.186275	0.28	17.14286							
51		Bladder	0.00302	0.0024	0.042857							
52		Breast	1.72549	3.8	24.57143							
53		Liver	1.186275	0.23	17.14286							
54		Esophagus (Thymus)	0.312745	1.8	4.971429							
55		Thyroid	0.032353	0.084	0.457143							
56		Skin	0.289598	0.3	3.714286							
57		Bone Surface	0.55	0.62	7.714286							
58		Brain	0.001402	0.0024	0.019714							
59		Salivary Glands (Brain)	0.017255	0.03	0.245714							
60		Remainder	0.39902	0.43	5.714286							
61		Not Applicable	0	0	0							
62	Remainder Organs (HT):	Adrenals	0.765596	0.13	10.85714							
63		Small Intestine	0.118627	0.034	1.714286							
64		Kidney	0.002598	0.00099	0.037143							
65		Pancreas	0.431373	0.12	6.285714							
66		Spleen	0.452941	0.11	6.571429							
67		Thymus	0.55	3.2	7.714286							
68		Uterus / Prostate (Bladder)	0.002598	0.00099	0.037143							
69		Muscle	0.293824	0.3	3.714286							
70		Gall Bladder	0.15098	0.042	2.085714							
71		Heart	2.150363	1.4	31.42857							
72		ET region (Thyroid)	0.002647	0.057	0.314286							
73		Lymph nodes (Muscle)	0.293824	0.3	3.714286							
74		Oral mucosa (Brain)	0.001402	0.0023	0.019429							
75	Other Organs (HT):	Eye lenses	0.004637	0	0.065714							
76		Testes	0.000291	0	0.004							
77		Ovaries	0.004529	0.000951	0.065714							
78		Uterus	0.003882	0.00092	0.057143							
79		Prostate	0.001294	0.001	0.018286							
80	Effective Dose (mSv)		0.657843	0.84	9.405871							
81	Total Effective Dose (mSv)										10.92641457	

FIG. 4. Schema of total dose worksheet. This worksheet saved data on scan conditions and doses.

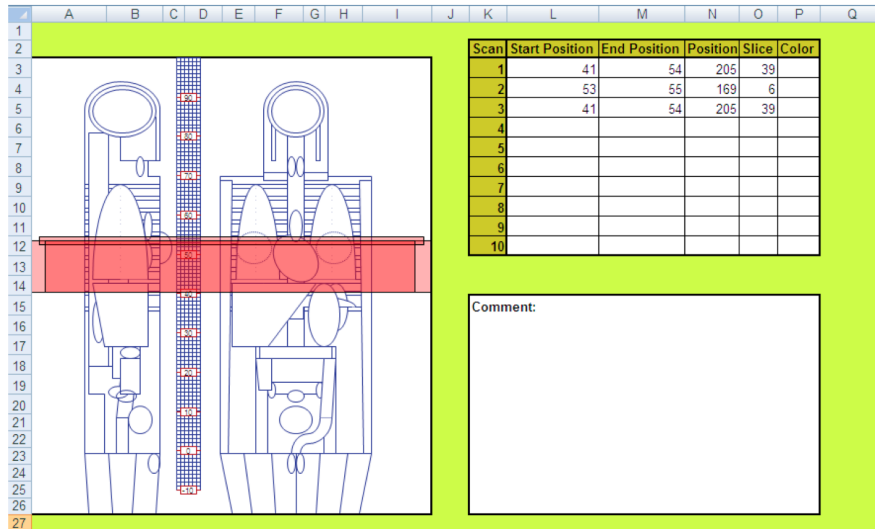


FIG. 5. Schema of total area worksheet. This worksheet saved data on scan range. The MIRD-5 mathematical phantom was divided from head to mid-thigh into 208 axial slabs of 5 mm thickness. The CCTA scanning area is shown on the phantom.

E. Input of CCTA scanning protocols

The organ- and tissue-absorbed doses and effective dose were estimated for the CCTA scanning protocols (Tables 2 and 3) to confirm the software reliability. These protocols included the following: tube currents of 90 mA for plane scans (target CTA) and 450 mA for contrast enhancement scans (prospective or continuous CTA), a scan length of 128 mm, and a bolus tracking scan time of 2.7 s. Average data were obtained from 50 patients (mean age, 69 ± 9.6 years; height, 161.5 ± 9.2 cm; weight, 62.4 ± 11.7 kg). The bolus tracking time was calculated as the total time of the intermittent scans and continuous scan. However, 320-MDCT is incapable of stopping the continuous scan automatically within 10 s for mechanical restriction. Therefore, we performed four intermittent scans (2.55 s total) to provide stable reproducibility of the bolus tracking scan time, as a continuous scan with a manual stop is not stably reproducible. The scan areas were then determined, as shown in Fig. 5. Note that a positioning scan was excluded from this assessment.

The effective dose was defined in ICRP Publication 103,⁽²⁶⁾ which used a more realistic description of the human body in the form of a voxel model phantom⁽⁸⁾ constructed from medical imaging data of a real person. However, the effective dose from ImPACT was estimated using the MIRD-5 phantom. Therefore, the reference phantom C.F., which links the MIRD-5 phantom to the ICRP 110 reference phantom,⁽⁸⁾ was used.⁽²¹⁾ The following concept, reported by Kobayashi and colleagues,⁽²¹⁾ was used to determine the reference phantom C.F.:

$$\text{Absorbed dose}_{ICRP\ 110} = \text{Absorbed dose}_{MIRD-5} \times \text{reference phantom C.F.} \quad (3)$$

$$\text{reference phantom C.F.} = \frac{\text{Absorbed dose}_{ICRP\ 110}}{\text{Absorbed dose}_{MIRD-5}} \quad (4)$$

The reference phantom C.F. includes 14 CT examination categories (chest, chest–pelvis, abdomen–pelvis, abdomen, pelvis, adrenals, liver, kidneys, liver–kidneys, kidneys–bladder, head, neck, and head–neck). During CCTA examination, we considered the chest C.F. to be appropriate.

TABLE 2. Scan protocol^a for a coronary CT examination at 60 bpm.

	<i>Dual Scanography</i>	<i>Volume (Target CTA)</i>	<i>Bolus Tracking</i>	<i>Volume (Prospective CTA)</i>
Tube voltage (kV)	120	120	120	120
Tube current (mA)	10	90	20	450
Tube rotation time (s/rot)		0.275	0.275	0.275
Scan length (mm)	400	128	2	128
Slice No	9-24	16-21	16	16-21
Field of view		320(M)	320(M)	320(M)
Scan time (s)			2.55	
Acquisition time (s)		0.275		
Cardiac phase (%)		75		70-80
Beat		1		1
CTDI _{vol} (mGy)		2.2	13.4	11.5
DLP (mGy•cm)		29.6	2.7	151.2

^a These scan protocols were obtained from the average data of 50 patients (mean average, 69±9.6years; height, 161.5±9.2cm; weight, 62.4±11.7kg).

TABLE 3. Scan protocol^a for a coronary CT examination at 90 bpm.

	<i>Dual Scanography</i>	<i>Volume (Target CTA)</i>	<i>Bolus Tracking</i>	<i>Volume (Continuous CTA)</i>
Tube voltage (kV)	120	120	120	120
Tube current (mA)	10	90	20	450
Tube rotation time (s/rot)		0.275	0.275	0.275
Scan length (mm)	400	128	2	128
Slice No.	9-24	16-21	16	16-21
Field of view		320(M)	320(M)	320(M)
Scan time (s)			2.55	
Acquisition time (s)		0.275		
Cardiac phase (%)		75		0-100
Beat		1		3
CTDI _{vol} (mGy)		2.3	8	93.0
DLP (mGy•cm)		28.9	1.6	1190

^a These scan protocols were obtained the average data of 50 patients (mean average, 69±9.6years; height, 161.5±9.2cm; weight, 62.4±11.7kg).

F. Comparison of radiation doses

TLDs were calibrated using an ionization chamber with a volume of 6 cm³ (10X5–6; Radcal Corporation, Monrovia, CA) and a dosimeter (9015; Radcal) that was annually calibrated by a standard dosimetry laboratory. TLDs were then calibrated at an air kerma of 10 mGy from an effective energy of 54.6 keV (half-value layer (HVL) of aluminum (99.9 %); 7.88 mmAl) using the above-described ionization chamber and diagnostic X-ray equipment (KXO-81; Toshiba Medical Systems, Otawara, Japan) with an X-ray tube aluminum filter (DRX-3724HD; 1.1 mmAl; Toshiba Medical Systems), collimation-filter (TF-6TL-6; 1.2 mmAl; Toshiba Medical Systems), and additional 6.0 mmAl filter (purity: 99.9%).

The phantom study used a human body phantom in which molded polymer shapes, intended to simulate bone, were embedded in a material equivalent to soft tissue (Alderson RANDO phantom with or without breasts; 175 cm, 73.5 kg; The Phantom Laboratory, Salem, NY); 233 TLD elements (MSO-S; Kyokko, Japan) were additionally inserted into this phantom. The RANDO phantom was placed in the supine position on a 320-MDCT table and irradiated to evaluate the radiation doses from CCTA (Tables 2 and 3). An individual C.F. was subsequently applied after measuring the amount of fluorescence (M) with a TLD reader (Model 3000;

Kyokko, Hiroshima, Japan). The air-absorbed dose D_{air} was calculated from the fluorescence (f), as indicated in Eq. (5):

$$D_{air} = M \times f [Gy] \quad (5)$$

The sex-averaged organ- and tissue-absorbed dose D (Gy) was calculated using D_{air} and the ratio of the air and organ mass energy-absorption coefficient (μ_{en}/ρ) at an effective energy of 54 keV, as follows:

$$D = D_{air} \times \frac{(\mu_{en}/\rho)_{soft\ tissue\ etc}}{(\mu_{en}/\rho)_{air}} [Gy] \quad (6)$$

The sex-averaged equivalent dose H_T (Sv) was then calculated using D and a radiation weighting factor (1.0) specified in the ICRP Publication 103:⁽²⁶⁾

$$H_T = D \times 1.0 [Sv] \quad (7)$$

The effective dose E (Sv) was calculated using H_T and the age- and sex-averaged weighting factor W_T for each organ or tissue:⁽²⁶⁾

$$E = \sum W_T \times H_T [Sv] \quad (8)$$

Regarding the remaining tissues and organs, the adrenal gland, gallbladder, heart, kidney, pancreas, prostate gland (for males), small intestine, spleen, and uterus (for females) were evaluated. The endosteal bone surface dose enhancement factors, referenced by Nishizawa et al.⁽²⁷⁾ for each bone type, were used.

In contrast, the effective dose was estimated according to the following equation for comparison with the k-factor study; specifically, the effective dose was calculated from the DLP displayed on the CT console and the k-factor for adult chest ($0.014 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$) from the 2004 European Commission Guidelines:⁽¹⁴⁾

$$E = DLP \times k\text{-factor} [Sv] \quad (9)$$

In addition, the effective dose was estimated using the C.F. values reported by Kobayashi et al.⁽¹⁹⁾ useful for coronary evaluation, as follows: volume scan, $0.031 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$, and bolus tracking, $0.017 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$.

III. RESULTS

A. C.F. evaluation

We first determined the C.F.s of cardiac applications (Ca score, target CTA, prospective CTA, continuous CTA/CFA, and CTA/CFA Modulation) according to Eq. (1) (Figs. 6 to 10). Figure 6 demonstrates that the Ca score C.F. is independent of the cardiac phase and HR. The C.F. increased with longer X-ray tube rotation times. Figure 7 demonstrates that the target CTA C.F. at an acquisition time of 0.275 s was the same as the Ca score C.F. In addition, other C.F. values increased linearly with an increasing acquisition time. Therefore, the target CTA C.F. remains independent of the cardiac phase and HR. Figure 8 shows a correlation of the prospective CTA C.F. with HR and cardiac phase ranges. The C.F. tended to increase as the

cardiac phase range widened. In addition, we clarified a limitation of the C.F. with respect to determining the cardiac phase range necessary for reducing the $CTDI_{with\ ECG}$. Accordingly, the cardiac phase limitation was characterized by HR (10% at 60 bpm, 15% at 80 bpm, and 20% at 100 bpm). To reduce the patient dose, the cardiac phase range should be kept as narrow as possible. If the prespecified narrow cardiac phase range exceeds these values, the patient dose will not be reduced. Figure 9 shows that the continuous CTA/CFA C.F., which increased as HR decreased, was one to four times higher than that of the C.F. value obtained for the Ca score in Fig. 6. Figure 10 shows the CTA/CFA modulation at a dose reduction of 50% and 25%. These C.F.s in the 70%–90% dose cardiac phase range were the same as the value obtained for continuous CTA/CFA. At 80 bpm, even the 50% cardiac phase range was equivalent to the value obtained for continuous CTA/CFA. The CTA/CFA modulation at a dose reduction of 50% reduced the dose in comparison with that at a dose reduction of 25%. The cardiac phase range had less of an influence on the dose as the dose reduction decreased. In other words, this value also increased as the dose increase phase range increased. A reference table of cardiac application data was created from these data (Fig. 4).

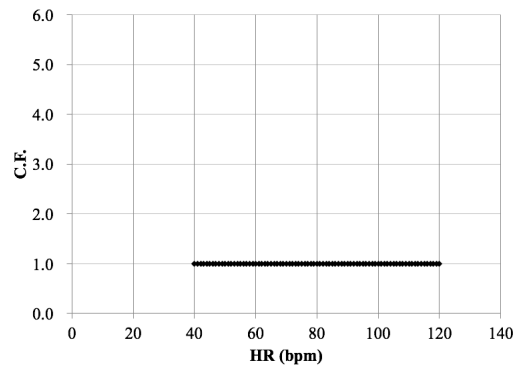


FIG. 6. C.F. ($CTDI_{with\ ECG}/CTDI_{without\ ECG}$) for the Ca score. CTDI was obtained from the CT console display for each of the scan protocols. The cardiac phase is 75% of the R-R interval (late diastole) for 40–60 bpm and 40% (end systole) for 70–120 bpm.

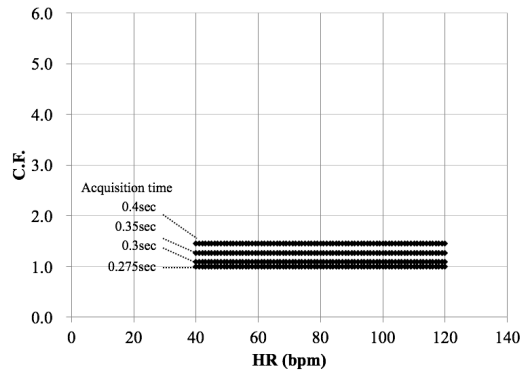


FIG. 7. C.F. ($CTDI_{with\ ECG}/CTDI_{without\ ECG}$) for target CTA. CTDI was obtained from the CT console display for each of the scan protocols. The tube rotation time was 0.275 s/rot.

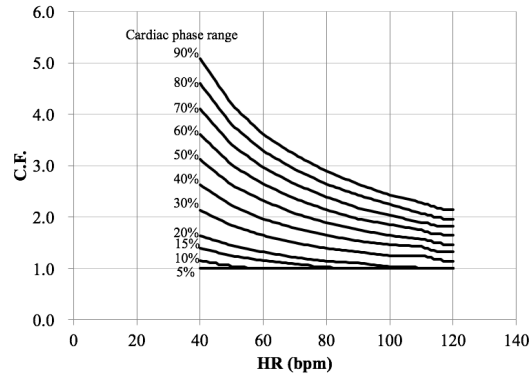


FIG. 8. C.F. ($CTDI_{with\ ECG}/CTDI_{without\ ECG}$) for prospective CTA CTDI was obtained from the CT console display for each of the scan protocols. C.F. is limited when determining the cardiac phase range required to reduce the CTDI (10% at 60 bpm, 15% at 80 bpm, and 20% at 100 bpm). If the narrow prespecified cardiac phase range exceeds these values, the patient dose is not reduced.

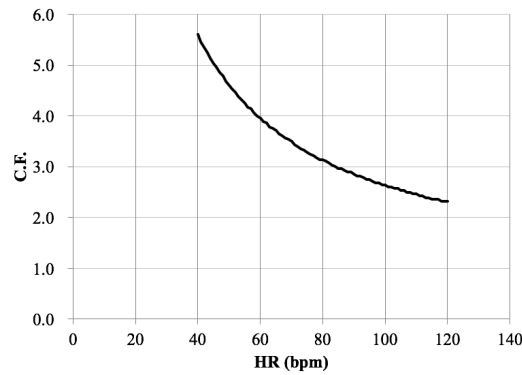


FIG. 9. C.F. ($CTDI_{with\ ECG}/CTDI_{without\ ECG}$) for continuous CTA/CFA. CTDI was obtained from the CT console display for each of the scan protocols. The C.F. was increased with decreasing HR.

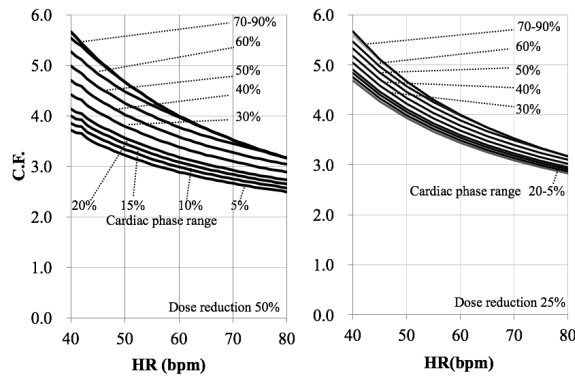


FIG. 10. C.F. ($CTDI_{with\ ECG}/CTDI_{without\ ECG}$) for CTA/CFA modulation. CTDI was obtained from the CT console display for each of the scan protocols. One heartbeat is short; tube current is not modulated for HR of 80 bpm or more.

B. Comparison of radiation doses

Table 4 shows the organ doses and the effective doses estimated by the ImPACT study and phantom study. Within the same examination, some organs received noticeably different doses between phantoms. For example, the doses to the breasts in the reference male phantom (10.66 mGy at 60 bpm and 75.77 mGy at 90 bpm) were approximately 60% less than those for the absorbed doses in the reference female phantom (17.50 mGy and 123.50 mGy). In contrast, the doses to the breasts for the reference person (14.08 mGy and 99.64 mGy) were similar to those in the phantom study (14.15 mGy and 101.66 mGy). In the CCTA examination, the breasts had the highest absorbed doses among all the organs. Similarly, the absorbed doses to the lung were high because this organ was directly irradiated during the bolus tracking scan (Fig. 5). Regarding the lung absorbed dose, the ImPACT study doses were 8.72 mGy at 60 bpm and 62.48 mGy at 90 bpm vs. 11.20 mGy and 78.88 mGy at 60 and 90 bpm, respectively, during the phantom study. After the breasts and lung, the highest absorbed doses were observed in the stomach, liver, and esophagus because these organs were partially irradiated by volume scans. Therefore, doses absorbed by these organs were much higher than those absorbed by nonirradiated organs, such as the colon, gonads, bladder, thyroid, brain, and salivary glands. Furthermore, the absorbed doses to the lung, stomach, and liver according to ImPACT differed from those obtained in the phantom study. The absorbed doses on the bone surface (3.42 mGy and 24.62 mGy vs. 1.42 mGy and 11.26 mGy) were approximately twofold higher than those obtained in the phantom study; however, the absorbed dose of the bone surface and bone marrow may have been inaccurate because of unclear tissue-absorbed dose measurements. The effective doses for the reference male phantom (4.04 mSv at 60 bpm and 29.03 mSv at 90 bpm) were approximately 25% less than those for the reference female phantom (5.28 mSv and 37.84 mSv), and the doses for the reference person (4.66 mSv and 33.43 mSv) were approximately 10% less than those for the phantom study (5.28 mSv and 36.68 mSv), with differences of 0.62 mSv (13%) and 3.25 mSv (10%), respectively (Table 5). The effective doses obtained with the k-factor ($0.014 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$; 2.57 mSv at 60 bpm and 17.10 mSv at 90 bpm) were significantly lower than those obtained with the other two types of measurements; for example, the differences from ImPACT were 2.09 mSv (45%) and 16.33 mSv (50%), respectively. In contrast, the effective doses obtained with the C.F. values reported by Einstein et al.⁽¹⁹⁾ (volume scan and bolus tracking scan at 0.031 and $0.017 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$, respectively; 5.65 mSv at 60 bpm and 37.81 mSv at 90 bpm) were more similar to those of the phantom study.

TABLE 4. Comparisons between different organ dose measurements.

Organ	ImPACT HR 60 bpm			ImPACT HR 90 bpm			RANDO HR 60 bpm	RANDO HR 90 bpm
	Male	Female	Person ^a	Male	Female	Person ^a		
Bone Marrow	1.83	2.33	2.08	13.18	16.71	14.95	1.56	11.49
Breasts	10.66	17.50	14.08	75.77	123.50	99.64	14.15	101.66
Colon	0.14	0.19	0.17	1.05	1.40	1.23	0.47	2.82
Lung	7.75	9.69	8.72	55.45	69.50	62.48	11.20	78.88
Stomach	7.22	6.82	7.02	52.65	49.98	51.32	7.47	63.97
Remainder	2.45	2.45	2.45	17.59	17.59	17.59	2.58	19.17
Gonads	0.01	0.01	0.01	0.11	0.05	0.08	0.10	0.58
Bladder	0.02	0.02	0.02	0.13	0.12	0.13	0.10	0.57
Oesophagus	2.13	2.67	2.40	14.25	17.81	16.03	4.30	19.36
Liver	7.22	8.93	8.07	52.65	64.96	58.80	8.79	52.55
Thyroid	0.20	0.23	0.21	1.41	1.59	1.50	0.98	3.72
Bone surface	3.31	3.53	3.42	23.75	25.48	24.62	1.42	11.26
Brain	0.01	0.01	0.01	0.06	0.10	0.08	0.07	0.51
Salivary glands	0.11	0.13	0.12	0.76	0.88	0.82	0.15	1.17
Skin	1.59	1.60	1.60	11.43	11.44	11.44	1.64	10.17

^a "Person" is sex-averaged reference person.

TABLE 5. Comparisons between different effective dose measurements.

Measurement	Effective Dose (mSv)	
	60 bpm	90 bpm
Modified ImPACT (male)	4.04	29.03
(female)	5.28	37.84
(person)	4.66	33.43
Phantom study (RANDO)	5.28	36.68
k-factor study (0.014 mSv•mGy ⁻¹ •cm ⁻¹)	2.57	17.10
(0.031 mSv•mGy ⁻¹ •cm ⁻¹)	5.65	37.81

IV. DISCUSSION

In this study, we have shown that modified ImPACT, when used to evaluate CCTA with cardiac applications (Ca score, target CTA, prospective CTA, continuous CTA/CFA, and CTA/CFA modulation), can assess radiation doses (CTDI, DLP, organ doses, and effective dose). We have additionally demonstrated that the CTDI can be characterized by cardiac applications (CTDI_{with ECG}). These results suggest that dose assessment with modified ImPACT is a practical method for CCTA evaluation.

In many dose estimations involving CCTA cases, the k-factor (adult chest; 0.014 mSv•mGy⁻¹•cm⁻¹) is used.⁽²⁾ However, we thought that the effective dose would be underestimated because the chest k-factor is obtained from a portion of the entire chest rather than the heart itself. The adult coronary k-factors were introduced by Einstein and colleagues⁽¹⁹⁾ and Gosling et al.⁽²⁸⁾ to assess the CCTA effective dose; these authors reported C.F. values of 0.027–0.034 and 0.028 mSv•mGy⁻¹•cm⁻¹, respectively. Although these adult coronary k-factors can assess the effective dose, they cannot assess the organ- and tissue-absorbed doses. Therefore, the effective dose for CCTA is possibly underestimated when the adult chest k-factor is used. In contrast, the absorbed doses are assessed easily with modified ImPACT.

An earlier study by Kobayashi et al.⁽²¹⁾ described a method combining both scanner and phantom data. Although that study provided evidence of the considerable flexibility of ImPACT, it still failed to demonstrate a correspondence with CCTA dose assessments. Therefore, the present study used C.F.-based methodology to assess CCTA radiation doses. The obtained C.F. results indicate that each cardiac application has particular dose characteristics, which could be explained by the following: 1) prospective ECG-triggering scans (Ca score, target CTA, and prospective CTA) are active only during a prespecified cardiac phase within the cardiac cycle, and 2) retrospective ECG reconstruction scans (continuous CTA/CFA and CTA/CFA modulation) are active throughout the entire cardiac cycle. Therefore, during Ca scoring, X-ray irradiation is only active for one X-ray tube rotation to obtain image data during a prespecified cardiac phase; thus the Ca scoring dose (CTDI_{with ECG}) is independent of the cardiac phase and HR. Target CTA features a similar X-ray irradiation activation pattern, and the resulting dose increases linearly as the acquisition time increases. During prospective CTA, X-ray irradiation is active for one or more X-ray tube rotations (i.e., single rotation) because the prespecified cardiac phase time exceeds one rotation time, and the resulting dose increases at low HRs with a wide prespecified cardiac phase range because the absolute time increases. However, in this study, we clarified a limitation of the prospective CTA dose when determining the cardiac phase range required for dose reduction. Therefore, narrow cardiac phase specification may not lead to dose reduction. During continuous CTA/CFA, X-ray irradiation remains active throughout the cardiac cycle, resulting in a much larger dose than that in other ECG-gated scans. The CTA/CFA modulation

dose over a wide cardiac phase range of 70%–90% is similar to the continuous CTA/CFA dose because the dose reduction phase time is too short to modulate the tube current. We confirm that the results of the present study are useful for determining scanning protocols in ECG-based examinations. Therefore, these results were subsequently used for the C.F. (Eq. (2)).

One limitation of modified ImpACT is that it reduces radiosensitive organs to simple geometric shapes. Therefore, the doses absorbed by the lung, stomach, and liver differed from those measured in the RANDO phantom study. According to ImpACT, the doses absorbed by the bone surface were twofold higher than those obtained in the phantom study. Although the tissue-absorbed doses in the phantom study were estimated using the method reported by Nishizawa and colleagues,⁽²⁷⁾ these doses may have been inaccurate because tissue-absorbed dose estimation has not been well reported.

Modified ImpACT yields a more accurate effective dose when compared with the k-factor method. In addition, the effective dose for the reference male phantom was approximately 25% less than those for the reference female phantom. We confirm that this difference is due to differences in the dose absorbed by the breasts. In contrast, the effective doses for the reference phantom were approximately 10% less than obtained in the phantom study. These results occurred because of differences in factors such as phantoms, organ locations, TLD sensitivity, TLD insert positions, and estimated tissue-absorbed doses. For example, the effective dose was approximately 7.5-fold higher at 90 bpm than at 60 bpm. However, the continuous CTA/CFA three-beat dose at 90 bpm was 8.4 (Fig. 9) because of overbeaming during each intermittent single-beat scan.

Finally, we consider the credibility of the C.F. values reported by Einstein et al.⁽¹⁹⁾ As reported in that seminal study, the heart C.F. is approximately twofold the adult chest k-factor. The present study, however, shows that modified ImpACT and Einstein's method identified similar effective doses.⁽¹⁹⁾ The greatest advantage of our study is the ability to perform absorbed dose. However, a potential weakness of the present study is that C.F. values were obtained only for the Aquilion ONE ViSION Edition scanner; therefore, we cannot extrapolate our findings to other scanners. In addition, the present study indicates the importance of an appropriate scan area when using the k-factor method, a problem that was previously noted by Shrimpton et al.⁽²⁹⁾ Using CCTA, we speculated that in comparison to the k-factor, the effective doses to the head or neck (orbit, middle ear, teeth, and face), chest (heart and breasts), and abdomen (liver and kidneys) would differ. Therefore, further studies of the k-factor are needed to assess the effective doses for all types of examinations.

V. CONCLUSIONS

The present study demonstrated that modified ImpACT could perform ECG-gated, scanning-based radiation dose assessments and may thus be useful in future applications.

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